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A. CANDU Nuclear Power Technology

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A.1 What does "CANDU" mean?

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CANDU (a registered trademark of Atomic Energy of Canada Ltd.) stands for **"Canada Deuterium Uranium"**. It is a pressurized heavy-water power reactor designed first in the late 1950s by a consortium of Canadian government and private industry. All power reactors in Canada are of the CANDU type (of varying vintage). It is also the power-reactor product marketed by Canada abroad.

The CANDU designer is AECL (Atomic Energy of Canada Limited), a federal crown corporation created in 1952. Over 150 private companies in Canada supply components for the CANDU system (see related FAQ). AECL takes the lead role in developing the markets and projects, while drawing in Canadian and off-shore partners. In general, AECL acts as project integrator; most of the revenues flow to private industry.

In 1987, as part of the centennial of engineering in Canada, the CANDU reactor was named one of the top ten engineering achievements in Canada in the past century by the Association of Consulting Engineers of Canada.

(The list also included the transcontinental rail network, the St. Lawrence Seaway, the De Havilland Beaver aircraft, the Trans-Canada telephone microwave network, the Bombardier snowmobile; the development of the Athabaska Oil Sands, the Polymer plant at Sarnia, Ontario, the Alouette communications satellite, and the Hydro-Quebec high-voltage transmission system.)

A.2 How does a CANDU reactor work?

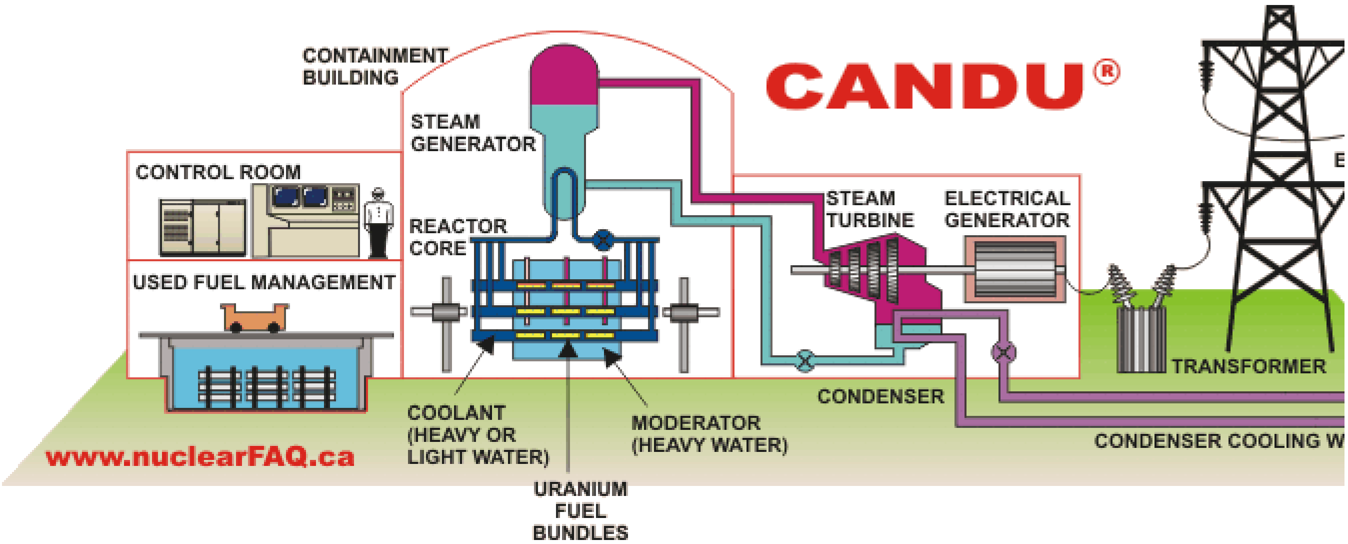
Fundamentally, a CANDU nuclear power plant generates electricity like most "thermal" electricity stations (i.e. those that use heat), which includes fossil-fuelled stations as well as most other commercial nuclear stations in the world: Heat is used to boil water, which turns to high pressure steam, which flows through a turbine, which turns an electrical generator, which makes electricity. Throughout this process, chemical energy (heat) is converted to kinetic energy and finally to electrical energy. (This can be compared, for example, with a hydraulic station, which converts the gravitational potential energy of water to kinetic energy, and then to electrical energy.)

The main difference between all the thermal stations is the source of heat. In fossil-fuelled stations the heat is generated by burning coal, oil, or natural gas. In a nuclear station the heat is generated by the **nuclear fission** of uranium (see related FAQ). As a source of industrial heat, nuclear fission has several advantages over fossil fuel burning (see related FAQs), but many of them stem from the fundamental fission process itself, which extracts millions of times more energy from a kg of fuel than any chemical reaction could (such as burning fossil fuels).

Although all nuclear plants in the world are based on the nuclear fission process, CANDU reactors are unique in many of the detailed engineering by which this process is implemented on an industrial scale:

Primarily, the CANDU reactor is a **heavy water** moderated reactor (see related FAQ). Heavy water is the key to many of the unique features of the CANDU design, including its ability to run on a variety of fuel types and many of its inherent safety features.

The CANDU design can use either **natural uranium** or **enriched uranium** fuel, and either **heavy water** (D2O) or **regular (or "light") water** (H2O) as coolant (the moderator and coolant are separate systems). It is **refuelled at full-power**, a capability provided by the subdivision of the core into hundreds of separate **pressure tubes**. Each pressure tube holds a single string of natural uranium fuel bundles (each bundle half a metre long and weighing about 20 kg) immersed in heavy-water coolant, and can be thought of as one of many separate "mini-pressure-vessel reactors" - highly subcritical of course. Surrounding each pressure tube a low-pressure, low-temperature heavy-water moderator fills the space between neighbouring pressure tubes.



(right-click on above image and choose "Save Target As..." to download high-res 9 MB version suitable for printing)

The cylindrical tank containing the pressure tubes and moderator, called the "calandria", sits on its side. Thus, the CANDU core is horizontal. A fuelling machine visits each end of the core, one fuelling and the other de-fuelling, allowing operators to insert fresh fuel at alternate ends for neighbouring fuel channels. From six to ten bundles are "shuffled" each day.

Axial flux-shaping is thus provided by fuel management, as is (to a certain extent) radial and azimuthal flux-shaping. Long-term reactivity control is also achieved through fuel management (ie, the ability to refuel on-line precludes the need for reactivity suppression over a core's life). Short-term reactivity control is provided by controllable light-water compartments, as well as absorber rods. (See related FAQ on CANDU reactor control.)

Thermalhydraulically, the core of most CANDU reactors is divided into two halves, with the divider line running vertically down the centre of the reactor face. Each half represents a separate coolant circuit. Heavy water coolant is supplied to the pressure tubes in each circuit via large headers at each end of the calandria, one pair of headers (inlet/outlet) for each half of the core. The subdivision of the core into two circuits, plus the fine subdivision into hundreds of interconnected pressure tubes, greatly reduces the effect of a potential LOCA (Loss-of-Coolant Accident).

See related FAQ for more discussion of CANDU safety.

Images...

- CANDU fuel bundle
- CANDU fuel bundle, another view
- Diagram of calandria and fuel bundle
- Diagram of CANDU-6 calandria
- CANDU calandria, prior to installation
- CANDU reactor face, showing end-fittings
- 3D Layout of a CANDU 6 reactor plant
- Schematic of a CANDU plant

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A.3 What is "nuclear fission"?

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Nuclear fission occurs when the nucleus of an atom splits into two or more pieces. This seemingly simple concept is actually quite a complex phenomenon that lay undiscovered for the first forty years of nuclear science. When eventually discovered at the outset of World War II, nuclear fission was immediately recognized as one of the most revolutionary, and (simultaneously) most potentially beneficial and destructive advances in the history of human development.

Understanding how nuclear fission works, however, requires a few introductory words about what holds everything around us together:

All matter is constructed from many billions of tiny atoms that are too small to be seen, even with an electron microscope: the tip of your index finger alone contains over 100 billion trillion atoms (that's a "1" followed by 23 zeroes). Atoms, in turn, consist of a central positively-charged "nucleus", surrounded by a cloud of negatively-charged orbiting electrons. The nucleus is very dense and contains most of the mass of any atom, and in fact it can be said that each atom (and thus matter itself) is mostly empty space. For example, if you could magnify the nucleus of a uranium atom to the size of a basketball, the corresponding distance to the neighbouring uranium nucleus would be about 6 km! The vast region in between would essentially have near-zero density (or near-vacuum conditions), and would carry a net negative charge.

The nucleus, in turn, is constructed of even smaller particles called "nucleons", which come in two main varieties: protons and neutrons. These two particles have roughly the same mass; however protons carry a positive charge and neutrons carry no net charge ("neutral"). A uranium nucleus contains over 230 protons and neutrons, which in the basketball analogy would each be about the size of a ping-pong ball.

Neutrons, as free particles outside of a nucleus, turn out to be quite useful tools for scientific research. Until their discovery in 1932, scientists had only positively-charged particles (e.g. protons, alpha particles) at their disposal for bombarding atoms and seeing what happened next. This required a great deal of energy since both the "bullet" particles and their "target" nuclei were positively charged, and nature doesn't let similar electrical charges get too close to each other (analogous to what happens when you try to push the similar poles of two magnets together). With the discovery of the neutron, however, scientists now had a particle that carried none of this electrical "baggage" - one that could enter a positively-charged nucleus at will, even with next to no energy.

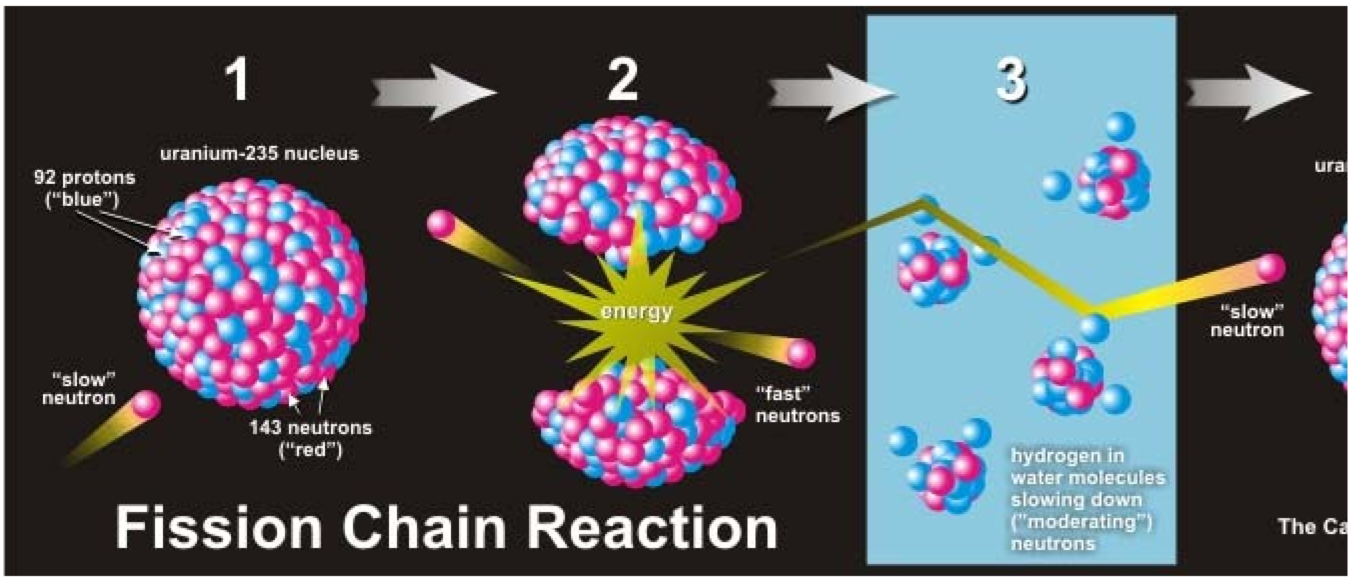
For years after the discovery of the neutron, this is exactly what many scientists around the world did. They believed that one of two possible things happened when a neutron entered a nucleus: it either bounced out again (usually in a different direction and often slowing down in the process), or it became absorbed by the nucleus and stopped. Both processes yield useful information and are still employed today in industry and science (e.g. neutron absorption is used to make life-saving medical radioisotopes (see *related FAQ*), and neutron bouncing (or "scattering") is used to improve the performance and safety of materials (see *related FAQ*).

If the nucleus absorbs a neutron it becomes heavier (by approximately the mass of a neutron), which usually makes it unstable. Nature's way of dealing with nuclear instabilities is to squeeze energy out of it until stability is achieved, and this process of emitting energy is called radioactive decay. With their new "neutron" tool, therefore, scientists could make hundreds of new, generally radioactive species of atoms, and the world of nuclear science in the pre-WWII years was exciting indeed.

What happened next, however, was nothing short of revolutionary. When scientists bombarded uranium with neutrons, in addition to making heavier atoms (which in itself was exciting since uranium was, until then, the heaviest atom found on earth), they realized - eventually - that they had caused some uranium atoms to split in half. They could tell this because when they examined the reaction products, the chemical signatures looked strangely similar to that belonging to atoms about half the size of uranium. The term "fission" was borrowed from the world of biology to describe this, and the rest is history.

In simple terms, nuclear fission occurs because large nuclei, like that of uranium, are about as big as nature can handle, so one more nucleon essentially becomes the straw that breaks the nuclear camel's back. This happens because any nucleus is held together by a tug of war between to powerful forces: one tending to glue it together and one tending to pull it apart. It so happens that the "glue" force (technically known as the "strong nuclear force") tends to get weaker as the diameter of a nucleus gets bigger, while the "pull apart" force (technically, the electrostatic repulsion from all the positively-charged protons in the nucleus) loses relatively little strength with distance. As nuclei get bigger and bigger, therefore, a point is reached where the "glue" force can no longer hold the nucleons to each other, and the atoms at this limiting size would therefore be the largest found in nature. The element whose atoms meet this description is uranium.

A nucleus of uranium has 92 protons, each wanting to get as far away from the others as possible. This is about as big a nucleus as the "glue" force can handle, and even then it's still a little bit too big, since uranium itself is a mildly unstable element (it radioactively decays, albeit at a very slow rate measured in the billions of years). Now, uranium comes in two versions: a smaller variety with 235 total nucleons (U-235), which means 92 protons and 143 neutrons; and a larger variety with 238 total nucleons (U-238), meaning 92 protons and 146 neutrons. Nuclei of any given element that differ this way in the number of neutrons are called "isotopes". It just so happens that although the smaller uranium isotope, U-235, is relatively sparsely distributed (less than 1% of all uranium in the ground), it accounts for most of the fissions in a nuclear reactor.



Which brings us to the question - what does nuclear fission have to do with making electricity? The answer lies in the fact that since fissioning a uranium nucleus is a way for nature to relieve a certain amount of "stress" involved in holding it together, it follows that some energy would be released in the process. It turns out that a lot of energy is released, several hundred million times more than the average chemical reaction.

What's more interesting is that a few other things are emitted when a uranium atom fissions, including two or three more neutrons. Since these are the same particles that cause a uranium nucleus to fission in the first place, the possibility exists to set up a "chain reaction" whereby uranium nuclei fission through collisions with neutrons, release a large amount of energy, and emit more neutrons that cause fissions in other uranium nuclei, and so on, and so on. The energy shows up mostly as heat that can be put to useful work, and this is how a nuclear power reactor works. A fraction of the fission energy shows up as high-frequency electromagnetic waves, called "gamma" radiation. Gamma radiation also emitted by the two remaining pieces of the uranium (the "fission products"), and hence nuclear reactors, and the fuel they discharge, must be shielded and properly handled.

The only remaining problem is that the neutrons emitted in each fission event are traveling far to fast (about 10% the speed of light) to initiate a significant number of new fission events. Since the chances of a uranium atom "catching" a neutron increases as the neutron speed decreases (for the same reason that it's easier to catch a lobbed softball than a 95 mph fastball), the neutrons must be slowed down. In a typical power reactor the neutrons are "slowed down" to a couple of km per second. This process is called "moderating" the neutrons, and the material used for this purpose is called a "moderator".

Moderating neutrons is actually quite simple: when neutrons bounce (or "scatter") off other nuclei, they tend to lose energy in the process, similar to how a billiard ball slows as it bounces around a billiard table. One of the best materials for this moderating process is ordinary water, since the hydrogen nuclei in water is similar in size to a neutron - and collisions with similar-sized objects can result in high energy loss per collision. This is how most of the world's power reactors slow, or moderate, their neutrons (another word for "regular" water is "light" water, and these reactors are classified broadly as "light water reactors", or LWRs).

Other moderators can be used: CANDU reactors, for example, make use of "heavy water", which is similar to light water but which does not absorb neutrons as readily (that is, in addition to slowing them down). If a reactor uses light water as a moderator, it needs to overcome this partial absorption by increasing the proportion of U-235 (the useful isotope) in the fuel by a factor of 4 to 7 - a process called "enrichment". Reactors using heavy water moderator, like CANDU, can use the uranium mixture as it is found in nature ("natural uranium"). To achieve this, however, CANDU reactors must use an "enriched" form of water, called "heavy water". (See *related FAQ*.)

NOTE: The above article provides a brief overview of the nuclear physics necessary to understand nuclear fission. For a more general introduction to the amazing world of "inner space", visit Lawrence Berkeley National Lab's excellent ABCs of Nuclear Science and Particle Adventure, which summarize the physics of radioactive decay and subatomic particle theory. For an excellent overview of nuclear and other areas of physics governing our natural world (including some great science fair ideas), visit Georgia State University's "HyperPhysics" website.

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A.4 What is "heavy water"?

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Heavy Water is the common name for D2O, deuterium oxide. It is similar to light water (H2O) in many ways, except that the hydrogen atom in each water molecule is replaced by "heavy" hydrogen, or *deuterium* (discovered by American chemist Harold Urey in 1931, earning him the 1934 Nobel Prize in chemistry). The deuterium makes D2O about 10% heavier than ordinary water.

Deuterium is a stable but rare isotope of hydrogen containing one neutron and one proton in its nucleus (common hydrogen has only a proton). Chemically, this additional neutron changes things only slightly, but in nuclear terms the difference is significant. For instance, heavy water is about eight times worse than light water for slowing down ("moderating") neutrons, but its macroscopic absorption cross-section (i.e. probability of absorption) is over 600 times less, leading to a *moderating ratio* (the ratio of the two parameters, a useful measure of a moderator's quality) that is 80 times higher than that of light water.

Heavy water's low absorption cross-section permits the use of natural uranium, which is low in fissile content and would not attain criticality in a light-water lattice. The lower slowing-down power of heavy water requires a much larger lattice than in light-water cores; however, the larger lattice allows space at the core endfaces for on-line refuelling, as well as space between channels for control rods, in-core detectors, and other non-fuel components.

In the past all of the heavy water for Canada's domestic and export needs has been extracted from ordinary water, where deuterium occurs naturally at a concentration of about 150 ppm (deuterium-to-hydrogen). For bulk commercial production, the primary extraction process to date, the "Girdler-Sulphide (G-S)" process, exploits the temperature-dependence of the exchange of deuterium between water and hydrogen-sulphide gas (H2S). In a typical G-S heavy-water extraction tower, ordinary water is passed over perforated trays through which the gas is bubbled. In the "hot section" of each tower the deuterium will migrate to the hydrogen-sulphide gas, and in the "cold section" this deuterium migrates back into cold feedwater.

In a multistage process, the water is passed through several extraction towers in series, ending with a vacuum distillation process that completes the enrichment to "reactor-grade" heavy water, nominally 99.75 wt% deuterium content.

During operation a CANDU plant will be required to periodically upgrade its inventory of heavy water (using again a vacuum distillation process), since a purity decrease of only 0.1 wt% can seriously affect the efficiency of the reactor's fuel utilization.

The G-S process, while capable of supplying the massive CANDU build programme from the late 1960s to the late 1980s, is expensive and requires large quantities of toxic H2S gas. It is thus a poor match for current market and regulatory conditions, and the last G-S plant in Canada shut down in 1997.

AECL is currently working on more efficient heavy-water production processes based on wet-proofed catalyst technology. CECE and CIRCE are based on electrolytic hydrogen and reformed hydrogen, respectively. CIRCE could be on the sidestream of a fertilizer or hydrogen-production plant, for example. AECL currently has a prototype CIRCE unit operating at a small hydrogen-production plant in Hamilton, Ontario. These catalyst technologies are more environmentally benign than the gas-extraction process they would replace. See "further reading" below for more details on the past and future of heavy-water production in Canada.

This process of "enriching" the moderator, rather than the fuel, is expensive and is part of the reason for the slightly larger capital cost of CANDU reactors compared to light-water reactors (heavy water represents about 20% of the capital cost). However, since the fuelling cost of a CANDU reactor is much lower than that of light-water, enriched-uranium reactors, the lifetime-averaged costs are comparable. Nevertheless, future CANDU designs will use about a quarter the heavy-water inventory for the same power output (see *related FAQ*), thus making their capital (up-front) cost more competitive.

Heavy water has an alternate attraction for scientists seeking the elusive *neutrino* particle. In Canada's Sudbury Neutrino Observatory (SNO) Project, about 1000 tonnes of heavy water are used as an interaction medium in which to track the passage of neutrinos from the sun. The heavy water is held in a large acrylic container two kilometres deep in the Canadian Shield, surrounded by photomultiplier detectors.

Further Reading...

- **"Heavy Water: a Manufacturers' Guide for the Hydrogen Century"** - The past and future of heavy-water technology in Canada, by heavy-water expert Dr. Alistair I. Miller of Atomic Energy of Canada Ltd. (PDF format, 340 kb).

Images...

- G-S heavy-water extraction tower
- Prototype CIRCE plant in Hamilton, Ontario.

A.5 How does a CANDU reactor refuel on-power?

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On-power refuelling is one of the unique features of the CANDU system. Due to the low excess reactivity of a natural-uranium fuel cycle, the core is designed to be continuously "stoked" with new fuel, rather than completely changed in a batch process (as in LWRs and BWRs). This reduces core excess reactivity, and the requirement for burnable poisons, which in turn increases fuel burnup (i.e., decreases the fuel throughput rate).

Other advantages of on-power refuelling include increased capacity factors (availability of the reactor), the ability to "fine-tune" the power distribution, the ability to detect and remove defective fuel, and a minimization of power perturbations due to refuelling.

On-power refuelling is achieved with two identical fuelling machines that latch on to opposing ends of a designated channel. Each machine, operated remotely from the control room, includes a magazine capable of either discharging new fuel or accepting spent fuel. With both machines latched on and brought up to system pressure, the ends of the fuel channel are opened up and new fuel is exchanged for old fuel - one machine discharging and the other accepting. The direction of fuelling is alternated in neighbouring channels to reduce asymmetries in the axial flux.

Both machines then disengage from the fuel channel, and the machine containing spent fuel travels to the discharge room, where it transfers its load to the spent fuel storage facility.

A channel is chosen for refuelling based upon several criteria, derived from both core-tracking simulation software and actual core instrumentation. The primary criterion is high burnup, but attention is also paid to minimization of the refuelling power "ripple", prevention of "hot spots", symmetry across the core, refuelling at alternate ends of the core, removal of experimental or defective bundles, maintaining an equal number of refuelled channels per zone, minimization of zone control level disparity, and striving for a uniform channel visit rate per week.

Images...

- CANDU on-power refuelling schematic

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A.6 How is fission energy converted to electrical energy in CANDU plants?

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In the CANDU design, as with the PWR design, the heat of fission is transferred, via a **primary water coolant**, to a secondary water system. The two water systems "meet" in a bank of **steam generators**, where the heat from the first system causes the second system (at lower pressure) to boil. This steam is then dried (liquid droplets removed, since they can damage turbine blades) and passed to a series of high-pressure and low-pressure **steam turbines**. The turbines are connected in series to an **electrical generator**. The primary water system, which becomes radioactive over time, does not leave the reactor's containment building.

It is a highly complex system from start to finish, involving a series of energy transformations with associated efficiencies. The potential energy of nuclear structure is converted first to heat via the fission process, then steam pressure, kinetic energy (of the turbine and generator), and ultimately to electrical energy.

The steam generators in CANDU plants differ from those in PWR plants, because their primary water system is different; besides the material itself (heavy water vs. light water), this applies to the chemistry, pressure, and temperature. CANDU steam generators were developed with aid from engineering companies in the United States, but on an independent track as dictated by the unique requirements of the CANDU process system.

John M. Dyke is a retired engineer who was intimately involved with the early design selection and development of CANDU steam generators. He has written a short essay, available here, recalling the interesting twists and turns that characterized this pioneering effort.

Most CANDU steam generators are U-bend tube-in-shell designs, with both an integral pre-heater section and an integral dryer centrifuge on top. This leads them to have a characteristic "light-bulb" shape.

Images...

- Photo of steam generator being installed at Darlington

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A.7 How many different CANDU designs are there?

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All CANDU reactors follow the same basic design, although variations can be found in most units. Power output in currently-operating units ranges from 125 MWe up to over 900 MWe, the main determinant being the number of fuel channels in the core. Ontario Power Generation (formerly Ontario Hydro) and Bruce Power units (all in the province of Ontario) tend to share a single containment system in a multi-unit station, while the commercial units sold to other Canadian utilities, as well as abroad, tend to have stand-alone containment like that found in other nuclear plant designs.

All of the CANDU units sold abroad by Atomic Energy of Canada Ltd. (AECL), with the exception of the early units sold to India and Pakistan, are of the "CANDU 6" design - with power output in the 700 MWe range. A larger design marketed by AECL is the ACR-1000, in the 1100 MWe range.

The ACR-1000 ("Advanced CANDU Reactor") is the next generation of CANDU reactors, currently being brought to market by AECL (see *related faq*). The ACR concept retains the fundamental features of CANDU design, while optimizing others to achieve higher efficiency and lower capital cost.

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A.8 How do CANDU reactors rank in performance against other designs?

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CANDU performance ratings (percentage of production against rated capacity) have traditionally led all other designs, primarily due to the on-line refuelling capability. In recent years PWR performance has improved, while some older CANDU units have suffered extended outages for projects like pressure-tube replacement. Today the average lifetime performance rating of the world-wide CANDU fleet is comparable to its nearest competitors (PWRs and BWRs), and over 10 points higher if one considers only the commercial CANDU 6 units that actually compete against PWR's in the market for new capacity.

The following table compares lifetime performance as of September 2004 for the six main reactor types, and one "other" category that includes units like the Indian CANDU-derivatives (the two bona fide Indian CANDU units are included in the CANDU category). Many thanks to Morgan Brown of AECL for supplying the numbers from which these averages were calculated, which he culled from the pages of *Nuclear Engineering International*, with added data from *Nucleonics Week*.

AVERAGE LIFETIME PERFORMANCE RATINGS (ALPR) TO Sep 30 2004, UNITS > 150 MWe
(percentage of electricity produced/rated capacity)

REACTOR TYPE	AVERAGE AGE (YR)	ALPR	# REPORTING
CANDU 6	11.8	85%	10
All CANDU	19.1	71%	31
PWR	21.0	74%	243
BWR	24.0	71%	92
RBMK	22.7	61%	13
MAGNOX	36.9	59%	8
AGR	21.4	62%	14
OTHER	13.6	64%	11

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A.9 How do CANDU reactors achieve high neutron economy?

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One of the distinguishing characteristics of the CANDU design is its high *neutron economy*, a term used to describe the efficiency with which a critical system uses neutrons. High neutron economy is essential to the viability of a natural-uranium fuel cycle. In the CANDU system neutron economy is maximized by:

- using heavy water and zirconium alloys as main constituent materials in the core (for low absorption),
- applying strict control of impurities in component materials,
- having a large-volume, low-temperature (70 deg.C) moderator, which permits thermalization to a low temperature (high fission cross-section) far from absorbing materials, and
- using on-power refuelling for long-term reactivity management. This means that there is no need to stock the core with enough excess reactivity to last a year or so without refuelling, as in other reactor designs, which also removes the need to add burnable poison to the core to suppress this reactivity early in the core's life.

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A.10 What fuel cycles can CANDU reactors adapt to?

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Its high neutron economy allows the CANDU design to potentially utilize a variety of different fuel cycles, including MOX and Th/U233 cycles (the latter, in one particular manifestation, achieving "near-breeder" status).

CANDU reactors can also burn spent PWR fuel, since the U-235 content in this fuel is still slightly enriched over natural fuel. The South Koreans are especially interested in this potential synergism between PWR and CANDU reactors, since they operate both types.

Recently, CANDU technology has been considered by the U.S. D.O.E. as a vehicle for denaturing weapons-grade plutonium declared surplus after the warming of the Cold War. See the next section for more details.

Another interesting fuel cycle option is the use of *Recovered Uranium*, which is a natural byproduct of LWR reprocessing. Recovered Uranium is about 0.9% enriched, and thus falls within the broader category of SEU (Slightly-Enriched Uranium - 0.9% to 1.2%) fuel cycles being considered for CANDU usage.

CANDU reactors may also play a role in fuel waste management, by being able to burn actinides without creating more actinides. In this strategy, waste actinides would be mixed within an inert matrix and burned in a CANDU core. As an efficient destoyer of waste actinides using currently-available technology, CANDU reactors can serve a role in reducing the total volume of high-level nuclear waste requiring long-term storage. Within an international strategy of nuclear fuel cycle centralization (currently a subject of global discussion), CANDU could reduce the total requirement for fast spectrum reactors needed for the final destruction process, while extending the time requirement for their development.

See also:

"The Evolution of CANDU Fuel Cycles and Their Potential Contribution to World Peace", by the J.J. Whitlock (2000).

"CANDU Advanced Fuels and Fuel Cycles", by P.G. Boczar et al (2002).

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A.11 What is CANFLEX fuel?

[A. CANDU Technology] [B. The Industry] [C. Cost/Benefit] [D. Safety/Liability] [E. Waste] [F. Security/Non-Proliferation] [G. Uranium] [H. Research Reactors] [I. Other R&D] [J. Further Info]

CANFLEX (***CAN****DU* ***Flex****ible Fuelling*) is an advanced fuel design developed by AECL since the mid-1980s. CANFLEX is similar in many ways to existing CANDU fuel, but incorporates several key modifications that improve the performance of the fuel. The CANFLEX bundle has 43 fuel pins instead of 37, and utilizes two different pin diameters. This reduces the power rating of the hottest pins in the bundles, for the same total bundle power output. Also, the CANFLEX design incorporates special geometry modifications that enhance the heat transfer between the fuel and surrounding coolant.

The use of CANFLEX fuel allows utilities to operate their CANDU reactors more efficiently, especially as they age. Point Lepreau recently participated in a co-operative program with AECL to test CANFLEX fuel under operational reactor conditions. Over a two-year period ending in August 2000, the Point Lepreau station derived energy from a total of 24 CANFLEX bundles (about 0.5% of a core load), as part of a programme to demonstrate viability of the concept in a working reactor.

CANFLEX is also the "carrier" of choice for introducing advanced fuel cycles into CANDU reactors (see related FAQ).

Bringing a new fuel design to the point of "in situ" testing is not a trivial process. The CANFLEX design has gone through a three-stage review and approval process, and was formally reviewed by a panel of industry experts. This was followed by a detailed review by utility staff, and a final review and approval from the Canadian Nuclear Safety Commission (CNSC, formerly known as the Atomic Energy Control Board, or AECB).

LATEST NEWS:

Bruce Power, a private nuclear operator (see *related FAQ*) operating the Bruce Nuclear plant on Lake Huron in Ontario, has recently announced a conversion to CANFLEX fuel at the Bruce plant, by 2006.

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A.12 What is AECL's next-generation "Advanced CANDU Reactor" (ACR)?

[A. CANDU Technology] [B. The Industry] [C. Cost/Benefit] [D. Safety/Liability] [E. Waste] [F. Security/Non-Proliferation] [G. Uranium] [H. Research Reactors] [I. Other R&D] [J. Further Info]

The **Advanced CANDU Reactor (ACR)** [1,2,3,4] represents the continuing evolution of CANDU design to match changing market conditions. ACR-1000 is the next-generation (officialy, "Generation III+") CANDU technology from Atomic Energy of Canada Ltd. (AECL), which maintains proven elements of existing CANDU design, while making some significant modifications:

- compact fuel-channel design, generating over 50% more power than a conventional CANDU-6 reactor, with approximately the same overall core diameter;
- improved thermal efficiency through higher-pressure steam turbines (13 MPa primary pressure; 7 MPa steam outlet pressure, vs. approximately 10 MPa and 5 MPa, respectively, in current designs);
- pressurized light-water coolant;
- negative coolant void reactivity;
- reduction in used fuel production by over 30%;
- greater thermal efficiency due to higher operating temperatures and pressures;
- reduced use of heavy water (more than half, for the same power output), thus reducing cost and eliminating many material handling concerns;
- use of slightly enriched uranium (1-2%) to extend fuel life to three times that of existing natural uranium fuel (reducing fuel waste volume by two-thirds);
- average channel power increased from roughly 6 MW (CANDU 6) to roughly 7 MW;
- flatter neutron flux shape, allowing 14% lower peak fuel element ratings;
- longer plant operational lifetime (60 years);
- longer operating cycles between maintanance outages (3 years);
- 90% design capacity factor;
- pre-stressed concrete containment (1.8 m thick) with steel liner; and
- further additions to CANDU's inherent passive safety.

At the same time the basic and defining design features of CANDU are all maintained:

- modular, horizontal fuel channel core;
- heavy water moderation;
- simple, economical fuel bundle;
- separate, cool, low-pressure moderatore with back-up heat sink capability;
- two independent, fast-acting shutdown systems;
- ability to perform long-term flux-shaping and failed fuel management through on-line refuelling.

It is expected that the capital cost of constructing these plants will be reduced by up to 40% compared to current plants. Contact AECL for more information.

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[1] J.M. Hopwood, "The Next Generation of CANDU Technologies: Profiling the Potential for Hydrogen Fuel", AECL publication available for download in PDF format (506 kb).

[2] J.M. Hopwood, J.W. Love, D.J. Wren, "The Next Generation of CANDU: Reactor Design to Meet Future Energy Markets", *Canadian Nuclear Society Bulletin*, Vol. 22, No. 3, October 2001.

[3] "ACR-1000 Technical Summary". AECL.

[4] ACR-1000 information webpage on AECL website.

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A.13 How are CANDU reactors controlled?

CANDU reactors are controlled by **two independent digital computers**, both monitoring plant status continuously but only one in control at any time (the other as backup).

Reactor shutdown occurs by two independent, fast-acting systems: Shutdown System 1 (SDS 1) consists of cadmium rods (28 in the CANDU-6 design) that drop by gravity into the core; Shutdown System 2 (SDS 2), in most CANDU designs, works by high-pressure injection of a liquid poison (gadolinium nitrate) into the low-pressure moderator. Each shutdown system is independently capable of shutting down the reactor safely, based on trip signals received through independent triplicated-logic detector systems. See related FAQ on CANDU safety systems in Section D.

In CANDU reactors built to date (e.g. CANDU 6), fine adjustments to the power distribution, as well as bulk reactivity control, are effected by a set of **Liquid Zone Controllers**. These are controllable light-water-filled compartments (14 in CANDU-6) located one per spatial "zone" of the core. Each controller is associated with two self-powered in-core flux detectors (28 in total for CANDU-6) responsible for characterizing the average flux in their associated zone. Absolute power levels are obtained by calibrating these signals against thermal measurements. In the CANDU-ACR design (see related FAQ) these fine adjustements are effected with **mechanical zone controllers**.

Long-term reactivity control and flux shaping are effected with **fuel-management**, since CANDU reactors can be refuelled on-line. In some CANDU designs flux-shaping is also possible with a set of **Adjuster Rods** (21 in CANDU-6), made of stainless steel or cobalt (this is how commercial cobalt-60 is manufactured in some Canadian CANDU units).

Another purpose of these Adjuster Rods is to extend the range of the regulating system in the positive direction (beyond that available from the liquid zone controllers). Extension of the range in the negative direction is provided by **Mechanical Control Absorbers** (four in CANDU-6), physically similar to the shutoff rods but not associated with the safety systems. These rods are used for rapid reduction in core power, at a rate or range unachievable with the liquid zone controllers.

In most CANDU designs, detailed **flux-mapping** throughout the core is achieved with a highly-distributed array of self-powered vanadium detectors (102 in CANDU-6). The mapping software uses this feedback, along with a database of known harmonics of possible CANDU flux shapes (normal and abnormal), to build up a three-dimensional picture of the neutron flux everywhere in the core. This information is used to continuously calibrate the zone control detectors, as well as provide empirical feedback to the fuel-management software.

Moderator poisons are not used for long-term reactivity control in CANDU reactors. Boron is used during initial fresh-fuel conditions (along with some depleted uranium fuel bundles for flux flattening). Gadolinium is used for xenon compensation following long shutdowns. Both these poisons are part of the moderator chemical control system, which is independent of the high-pressure nozzle injection system used for Shutdown System 2.

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A.14 How is core refurbishment part of CANDU life management?

CANDU reactors, like automobiles, are designed to have major components replaced during their lifespan. From the first prototype (NPD, 1962) to the latest CANDU 6, CANDU 9, and CANDU ACR designs, removal and replacement of pressure tubes, calandria tubes, feeder tubes, and other primary system "plumbing" has been an important part of plant life management.

The primary reason for this is the limited life of these components under the harsh conditions of reactor operation. Zirconium alloy pressure tubes, in particular, are bombarded intensely by neutrons under immense heat and pressure. Although the zirconium alloy is a robust material, chosen for its survivability under these very conditions, it does experience life-shortening metallurgical changes (e.g. pressure tubes grow several inches during their time in the reactor, and at the same time become more brittle). The monitoring of this situation is an on-going process throughout the reactor's life, and at any time a given pressure tube can be removed for inspection and replacement.

Eventually a point is reached, roughly mid-way in the life cycle, where large-scale replacement of these primary components becomes necessary. The Pickering-A station near Toronto, Ontario went through a complete pressure-tube replacement program in the 1980s, and has had major further refurbishment completed on two of its units. (See also this related FAQ.)

The Pt. Lepreau station in New Brunswick will soon undergo similar refurbishment that will see its useful lifetime extended by another 25 to 30 years. Pt. Lepreau currently supplies one-third of the electricity demand in New Brunswick. In the case of Pt. Lepreau, the refurbishment will include all pressure and calandria tubes, end-fittings, and feeders, and will take place over an 18-month outage planned from April 2008 until September 2009, at a estimated cost of $1.4 billion.

In October 2005 Bruce Power announced the refurbishment of its four-unit Bruce-A station, starting with a return-to-service project involving Units 1 and 2 that will give them 25 years of operating life. This will be followed by a life-extension refurbishment of Units 3 and 4. (See also this related FAQ.)

In June 2006 AECL announced the refurbishment of South Korea's Wolsong-1 CANDU plant, with shutdown scheduled in 2009.

Specific Websites for CANDU Refurbishment Projects:

- Pickering Unit 1
- Bruce A
- Point Lepreau

End of Section A